Exploring the Versatile Applications and Optimization Challenges of Wiegand Energy Harvesters: A Review

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Abstract— **Self-powered sensors are integral to the advancement of the Internet of Things (IoT), wireless sensor networks, unmanned vehicles, smart cities, and other sustainability initiatives. This review sheds light on the operational principles, materials, manufacturing processes, output characteristics, and potential applications of Wiegand sensors. A Wiegand sensor consists of a magnetic-sensing wire, known as a Wiegand wire, and a pick-up coil that is responsible for converting magnetic flux changes into electrical signals and energy. This requires an external magnetic field reversal to induce flux changes in the Wiegand wire, resulting in an output pulse in the pick-up coil. This output pulse is the product of the large Barkhausen effect, which renders the sensor performance independent of triggering and sensing frequencies. The main objective of this review is to provide a thorough overview of research on the Wiegand sensors. This section outlines current research findings and identifies potential application scenarios. Moreover, this review highlights any gaps in the existing literature and suggests directions for future research. Ultimately, the study offers insights into perspectives and research opportunities within the field of Wiegand sensors.**

Index Terms—**Wiegand sensor, Energy Harvesting, Internet of Things.**

1. Introduction

In the realm of sensing technologies, various energy forms, including thermal, mechanical, electrical, electromagnetic (EM) radiation, magnetic, and chemical energies, are utilized for measurement purposes. Magnetic sensing technologies offer distinct advantages such as non-contact operation, low power requirements, superior energy efficiency, high sensitivity, and robust reliability in adverse environments. These benefits drive the advancement of emerging technologies across manufacturing, transportation, communication, the economy, and sustainability efforts.

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Common magnetic sensors such as Hall sensors, magnetoresistance (MR) sensors, flux gate sensors, magnetoimpedance (MI) sensors, and the Wiegand sensor. Notably, the Wiegand sensor stands out as the only magnetic sensor, apart from inductive coils/variable reluctance sensors, capable of self-powering and autonomous operation for both sensing and energy harvesting simultaneously.

Named after its inventor, John R. Wiegand, the Wiegand sensor was extensively investigated in the 1970s [1-3] for diverse applications. It comprises a ferromagnetic wire known as a Wiegand wire and a pick-up coil wound around or placed close to the Wiegand wire. This setup allows for the generation of electrical signals while simultaneously harvesting energy.

To induce an output pulse with a duration typically ranging from 10 to 30 microseconds (μs), an optimal external magnetic field of around 30 to 110 Gauss (G) is required, often set at approximately 70 G. This external magnetic field triggers the magnetic reversal of the Wiegand wire, resulting in a large Barkhausen jump and generating an output pulse in the pick-up coil via Faraday's law of electromagnetic induction. Consequently, the sensor output depends solely on the magnetism and magnetic materials of the Wiegand wire, independent of the triggering and sensing frequency of the external field.

While the discovery of the Wiegand sensor did not spark widespread research in the 1980s, recent years have witnessed a rapid surge in adoption and extensive applications owing to the demand for energy-self-sufficient and maintenance-free devices in sensing networks and sustainability initiatives [4]. Current research efforts on Wiegand sensors focus on materials, design, assembly configuration, circuit optimization, and application scenarios, aiming to enhance their unique advantages and properties. Thorough reviews of Wiegand technology promote interdisciplinary understanding and unlock its potential.

This review paper is organized into subsections covering the working principles and reversal behaviors of the Wiegand effect, improvements in circuits, scenarios involving magnetic field sensing, integration of energy harvesting systems with Wiegand sensors, and discussions on future trends using various permanent magnets (PMs) to trigger output pulses. Finally, the main niches and suggested research directions for expanding Wiegand technology are outlined and concluded.

2. Working Principle

The mechanical process used to produce Wiegand wires creates a combination of magnetically hard and soft layers in the wire, causing the wire to exhibit high magnetic hysteresis. The Wiegand wire retains its initial polarity as the external magnetic field changes. However, when the strength of the external field reaches a critical threshold, the polarity of the magnetically soft layer of the Wiegand wire suddenly reverses. As the external field strengthens, the magnetically hard layer reverses its polarity so that the whole wire reaches a new magnetic state. When the external field returns to its original polarity, a sudden reversal of the soft material occurs. The wire will eventually return to its earlier state.

These fast reversals in the magnetic polarity of the wire core induce short pulses of electrical current in the fine copper coil wrapped around the Wiegand wire.

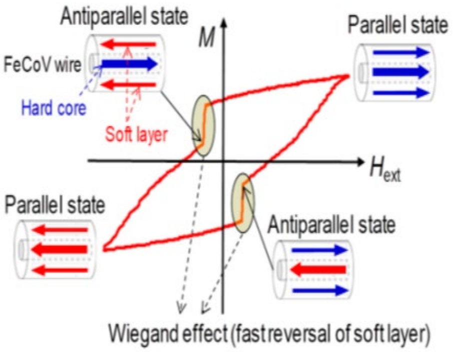

Fig.1. Working principle of the Wiegand sensor [5].

3. Application Scenarios of The Wiegand Sensor

A. *Sensing*

Although the necessity of a triggering field with appropriate intensity to switch the set-reset states of the Wiegand wire may impose limitations on magnetic field sensing capabilities, the inherent self-powered nature and triangular pulses of the output render the Wiegand sensor particularly well-suited for self-sufficient mechanical motion sensing. This feature, coupled with its rate-independent property, makes Wiegand sensors ideal for applications requiring zero-speed transducers. Currently, Wiegand sensors have been successfully adopted in various industrial practices, serving as tachometers, flowmeters, and proximity switchers.

Advanced motion-sensing and positioning applications leverage magnetic circuit design for event-triggering, facilitating detection, recording, and counting tasks using comparator, counter, and evaluation circuits. However, the arrangement, assembly, and machining precision of components play crucial roles in determining the resolution, accuracy, and tolerance of sensing and positioning systems. Furthermore, owing to the Wiegand sensor's robustness against adverse environments and its self-powered nature, its applications in drilling assembly and intra-body object placement in medical devices have been explored. Lien et al. [6] demonstrated that positioning repeatability of 0.3 μm can be achieved using a Wiegand sensor. In addition, energy harvesting can be seamlessly integrated through the Wiegand sensor based on the alternating polarities of the magnetic positioning system.

B. *Energy Harvesting*

F. Ongaro, S. Saggini, L. Corradini [7] explore two operational modes: one-shot pulse generation and continuous scavenging, focusing on their application to on-board battery charging.

J. Chotai et al. [8] designed a single-bit self-powered digital counter that utilizes Wiegand sensors and discussed its potential use in flow meters.

Pablo et al. [9] studied mechanical energy harvesting for rail axles, emphasizing the need for high miniaturization in harsh railway environments, especially near bogies and axles. They suggested Wiegand sensors as a possible solution to power Wireless Sensor Networks (WSN).

Yi-Hsin Chen et al [10] proposed an energy harvester that combines an eccentric pendulum with Wiegand wires to convert kinetic energy into electrical energy for powering sensors, specifically targeting Tire Pressure Monitoring Systems (TPMS). They found that connecting two Wiegand wires in series increases the electrical power generation to 0.88–1.24 mW during rotations of 240–660 rpm.

Chang et al. investigated the application of Wiegand sensors in linear magnetic positioning systems [11].

Jonas Wiegner et.al. developed a prototype IoT sensing device powered by Wiegand energy harvesting and demonstrated its capability for data acquisition, processing, and wireless transmission. They note that the current design requires a finite change in the external magnetic field and hence a limited range of movement to avoid large losses due to self-discharge [12].

Wiegand energy harvesters rely on repeated relative movements to switch between set and reset states, making them particularly suitable for vibrating devices and vehicles. A stroke amplitude of 0.6 mm in a reciprocally vibrating NdFeB magnet is sufficient to trigger an output pulse for a Wiegand sensor, with an optimal stroke amplitude of approximately 3 mm. Designs that consider both mechanical mechanisms and magnetic circuits are essential for dynamic stability and energy efficiency.

Wiegand sensors can assist in powering patternless devices, which is crucial for applications in Industry 4.0, Internet of Things, wireless sensor nodes, unmanned vehicles, smart cities, and sustainability efforts. Interdisciplinary challenges in materials, mechanical assembly, and electrical and magnetic circuits are encountered in the research and development of these applications. The proper design and optimization of harvesting systems with suitably scaled-up Wiegand sensors illustrate their promising feasibility and potential.

Furthermore, Wiegand energy harvesters enable wireless power transmission for low-power devices, which is particularly important for implantable micro-devices [13-18]. Their frequency-independent output and miniature size offer advantages over near-field resonant inductive coupling, particularly in terms of health and safety concerns related to electromagnetic fields. However, the control and management of stray fields must be considered, and alternatives to rare earth permanent magnets have been suggested to mitigate sustainability and EMI issues. Exploring alternative permanent magnet (PM) materials and optimizing magnetization techniques are critical steps toward wider adoption of Wiegand sensors.

4. Conclusion And Future Scope

This article provides an in-depth examination of Wiegand sensors, including their working principles, output properties, and applications. The output mechanism of the Wiegand sensors relies on the magnetostatic bias-induced large Barkausen effect. Their self-powered nature and miniature size position them as unconventional solutions to energy efficiency and sustainability concerns in emerging technologies. Notably, the remarkable repeatability and changing-rate independence of their output pulses make them promising candidates for novel micro-scale energy harvesting devices, which are crucial for wireless sensing and intelligent technologies.

The review identified several areas for further research and development:

Standardized metrics are needed to characterize the output behaviors and facilitate the comparison and verification of Wiegand sensors. Interdisciplinary efforts are essential for establishing these metrics, particularly as Wiegand sensors are widely adopted.

In-depth studies on the underlying magnetism and magnetic material behaviors of the Wiegand effect can yield both academic and industrial contributions. Understanding micro-magnetics and micro-wire behavior can unlock new research directions, including the integration of Wiegand sensors into micro-electromechanical systems (MEMS).

Exploration of new material processing techniques is crucial for expanding the range of materials capable of realizing the Wiegand effect. Interdisciplinary expertise is required for design optimization and to overcome technical limitations in application scenarios.

Investigating the coupling of Wiegand energy harvesters with supercapacitor presents an intriguing opportunity to create ultra-long-life power sources. This integrated approach requires further study to optimize the system performance.

Designing magnetic circuits tailored to the size-critical geometry of Wiegand sensors can enhance their adoption while addressing electromagnetic shielding and crosstalk issues that are commonly encountered in rare earth permanent magnets.

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